

# Chiral Corrections to Baryon Electromagnetic Form Factors

Robert J. Perry, Manuel E. Carrillo-Serrano, Anthony W. Thomas

*CSSM and ARC Centre of Excellence for Particle Physics at the Tera-scale, Department of Physics, University of Adelaide, Adelaide SA 5005, Australia*

## Abstract

Corrections motivated by chiral symmetry arguments have long been known to give important contributions to hadronic observables, particularly at low momentum transfer. It is possible to separate these approaches into two broad groups; either the corrections are implemented at the *parton level*, or at the *hadron level*. We explore the results of incorporating pion loop corrections at the hadron level to a calculation of electromagnetic form factors in the NJL model. These calculations are compared with the result of an earlier implementation of pion loops at the parton level using the same NJL model formalism. A particular parameter set yields a good description of low energy nucleon properties within both approaches. However, for the  $\Sigma^-$  there is a remarkable improvement when the chiral corrections are implemented at the hadronic level.

**Keywords:** chiral symmetry, electromagnetic form factors, NJL Model, pion corrections

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## 1. Introduction

The elastic electromagnetic form factors of a hadron are of great interest since they are related to the distributions of charge and current within the particle. They therefore give vital information about the structure of the hadron in question. As a consequence, improved measurements of the nucleon electromagnetic form factors have been the subject of many ongoing experimental programs. While much good data exists for the proton, shorter lifetimes and lack of free targets makes measurements of the neutron and other members of the spin- $\frac{1}{2}$  baryon octet more difficult.

After the discovery of QCD, early theoretical studies of these form factors were based on quark models, ranging from constituent quark models [1, 2] to the MIT bag model [3], with more recent studies employing the Schwinger-Dyson formalism [4]. The Nambu–Jona-Lasinio (NJL) model has also been widely used [5, 6] and in this paper the quark model component of the calculation will be based on earlier work [7, 8] using the NJL model with proper-time regularization [9] to simulate confinement.

The importance of chiral symmetry, especially for low energy hadron properties, was first recognised more than 50 years ago in the context of soft pion theorems [10], while its modern realization is based upon the chiral symmetry of QCD itself [11], with the pion as a pseudo-Goldstone boson, which becomes massless as the  $u$  and  $d$  masses tend to zero. While almost no-one now doubts the importance of chiral symmetry and particularly the inclusion of the pion as an explicit degree of freedom in any quark model calculation, there are still important differences between the

ways this is implemented. Here we study the significance of these differences for the nucleon,  $N$ , and  $\Sigma$  baryons.

## 2. Implementations of Chiral Symmetry

It is straightforward to understand the correct way to implement chiral symmetry. In the chiral limit the pion is massless and so a virtual pion can travel infinitely far from its source, *provided* the source mass does not change. That is, the process  $p \rightarrow n\pi^+$  has infinite range and hence the proton charge radius becomes infinite. However, the pion in the process  $p \rightarrow \Delta^0\pi^+$  is limited to the range  $1/\Delta M$ , where  $\Delta M$  is the  $\Delta - N$  mass difference in the chiral limit (which is similar to the empirical value).

Although simple and completely model independent, this argument is often lost in the technicalities of building a quark model. For example, it is common in spectroscopic studies to introduce pions into the quark model Hamiltonian as [12]

$$H_{\text{int}} = \frac{g^2}{(4\pi)^2} \frac{1}{3} \sum_{i < j} \vec{\sigma}_i \cdot \vec{\sigma}_j \vec{\tau}_i \cdot \vec{\tau}_j \times \left( m_\pi^2 \frac{e^{-m_\pi r_{ij}}}{r_{ij}} - 4\pi\delta(r_{ij}) \right), \quad (1)$$

where  $m_\pi$  is the pion mass. Such models include *only* the exchange of pions between different quarks. As shown by Thomas and Krein [12, 13], this leads to a very large error in the model independent leading non-analytic piece of the self-energies of the  $N$  and  $\Delta$  baryons, with the  $N/\Delta$  ratio being 5 in this model and 1 in chiral perturbation theory, evaluated as it must be at the *hadron level*.

In contrast to this, the use of the *parton level* approach in previous works has often been motivated by the chiral

quark model of Georgi and Manohar [14]. There one often finds pion loops evaluated on individual quarks, rather than on the hadron as a whole. It is not hard to see that this will also yield the wrong infrared behaviour as a function of quark mass. For the proton charge radius, for example, the process  $u \rightarrow d\pi^+$ , where  $u$  is a valence quark in the proton, may leave the three valence quarks ( $udd$ ) spectator to the pion with either spin one half or three halves. As explained above these give rise to totally different behaviour for the long distance pion cloud. However, there is no way to keep track of those differences if one focusses just on the parton, ignoring its environment.

While the LNA behaviour of an observable is a valuable tool for tracking whether a calculation is formally correct, in practice the total pion cloud contribution to a particular observable may or may not be a bad approximation. Our aim is to investigate the practical difference in some interesting examples. In particular, we take the NJL model calculations of the octet electromagnetic form factors of references [15, 16, 17], without pion loops, as the bare quark model. We then compare the results for low momentum transfer, including charge radii and magnetic moments, when the pion corrections are performed at the hadron level and at the parton level.

### 3. Baryon Form Factors in the NJL Model

The NJL model [18, 19] is a well known constituent quark model. The Lagrangian density for the  $SU(3)$  flavour NJL Model, in its Fierz symmetric form is given as [17]

$$\mathcal{L} = \bar{\psi}(i\not{\partial} - \hat{m})\psi + \frac{1}{2}G_\pi[(\bar{\psi}\lambda_i\psi)^2 - (\bar{\psi}\gamma_5\lambda_i\psi)^2] - \frac{1}{2}G_\rho[(\bar{\psi}\gamma^\mu\lambda_i\psi)^2 + (\bar{\psi}\gamma^\mu\gamma_5\lambda_i\psi)^2], \quad (2)$$

where  $\hat{m} = \text{diag}(m_u, m_d, m_s)$  and  $\lambda_i$  are the eight generators of  $SU(3)$  in the Gell-Mann representation, plus  $\lambda_0 = \sqrt{2}/3$ .

Previously, electromagnetic form factors were calculated in the NJL Model [16, 17], where baryons are naturally described as quark-diquark bound states [16]. The electromagnetic form factors are defined by the matrix elements of the electromagnetic current  $j^\mu$ :

$$\langle p', s' | j^\mu | p, s \rangle = \bar{u}(p', s') \left[ \gamma^\mu F_1^B(Q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2m_B} F_2^B(Q^2) \right] u(p, s), \quad (3)$$

where  $p$  and  $s$  designate the momentum and spin states of the baryon,  $B$ . Note that, as is conventional in the literature,  $Q^2 = -q^2$ . In the implementation of the NJL Model used here, the quark-photon vertex is dressed by including contributions from vector meson dominance. Of particular relevance for this paper, that work also showed the effects of pion loops calculated on the individual valence quarks.

It is common to use the Sachs parameterization of the electromagnetic form factors, which are given as linear combinations of  $F_1$  and  $F_2$ ;

$$G_E^B(Q^2) = F_1^B(Q^2) - \frac{Q^2}{4m_B^2} F_2^B(Q^2), \quad (4)$$

$$G_M^B(Q^2) = F_1^B(Q^2) + F_2^B(Q^2). \quad (5)$$

In this parameterization,  $G_E^B$  and  $G_M^B$  evaluated at  $Q^2 = 0$  are the electric charge and magnetic moment of the particle. One may also extract the electric charge radius from the slope of  $G_E^B$  at  $Q^2 = 0$ . The magnetic moments and electric charge radii are well known low energy observables, even for the shorter lived spin- $\frac{1}{2}$  baryons, and thus help to quantify the accuracy of the low  $Q^2$  predictions for the electromagnetic form factors in any model. Importantly, it is at low momentum transfer where pions are expected to contribute most and thus differences between the implementation of chiral symmetry are expected to be most clear.

### 4. Chiral Corrections

For our present purposes the light-front cloudy bag model (LFCBM), developed by Miller [20] is a suitable formalism for calculating the pion cloud corrections to baryon form factors. As in the original cloudy bag model [21, 22, 23, 24], in the LFCBM the pion corrections are evaluated at the hadron level and therefore ensure the correct LNA behaviour. Whereas Miller employed a quark model developed by Schlumpf [25], as noted earlier we use the NJL model. Within Miller's approach, using pseudoscalar coupling of the pion to the hadron, one obtains three Feynman diagrams at one loop order, as shown in Fig. 1.

The first diagram (Fig. 1a) is simply the quark model result, while the chiral corrections to these form factors are provided by the diagrams shown in Figs. 1b and 1c. As the name of the model suggests, these equations are evaluated on the light front, but importantly, since the form factors  $F_1$  and  $F_2$  are Lorentz invariant scalar functions, it is entirely consistent to take the results of the NJL model as input here. The results of that work are summarized

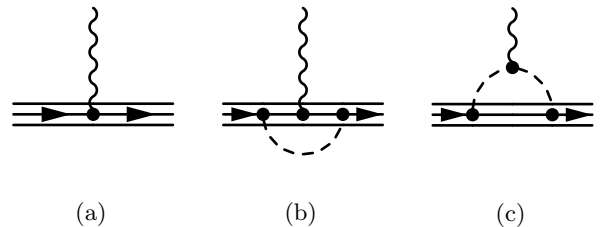


Figure 1: Diagrams which contribute to the calculation of electromagnetic form factors. Note that contributions from  $\Delta$  intermediate states are not considered in this calculation.

here as<sup>1</sup> [26]:

$$F_i^H(Q^2) = Z[F_{i,a}^H(Q^2) + F_{i,b}^H(Q^2) + F_{i,c}^H(Q^2)], \quad (6)$$

where  $i = 1, 2$ ,  $H$  is the hadron in question,  $a$ ,  $b$  and  $c$  refer to diagrams 1a, 1b and 1c, respectively, and  $Z$  is the wavefunction renormalisation constant, defined to ensure

that the charge of the proton is unity.

Evaluation of diagrams given in Figs. 1b and 1c lead to

$$F_{1,b}^H(Q^2) = \frac{g_{NN\pi}^2}{(4\pi)} \int_0^1 dx x \int \frac{d^2 L}{(2\pi)^2} \left[ F_1(Q^2) \left( L^2 + x^2 m_N^2 - \frac{1}{4} x^2 Q^2 \right) - F_2(Q^2) \left( \frac{x^2 Q^2}{2} \right) \right] \frac{1}{D(\vec{L}_+^2, x) D(\vec{L}_-^2, x)}, \quad (7)$$

$$F_{2,b}^H(Q^2) = -\frac{g_{NN\pi}^2}{(4\pi)} \int_0^1 dx x \int \frac{d^2 L}{(2\pi)^2} \left[ F_1(Q^2) (2x^2 m_N^2) + F_2(Q^2) \left( L^2 + x^2 m_N^2 - \frac{1}{4} x^2 Q^2 \right) \right] \frac{1}{D(\vec{L}_+^2, x) D(\vec{L}_-^2, x)}, \quad (8)$$

and

$$F_{1,c}^H = \frac{g_{NN\pi}^2}{(4\pi)} I_\tau F_\pi(Q^2) \int_0^1 dx x \int \frac{d^2 K}{(2\pi)^2} \left[ K^2 + x^2 m_N^2 - \frac{1}{4} (1-x)^2 Q^2 \right] \frac{1}{D(\vec{K}_+^2, x) D(\vec{K}_-^2, x)}, \quad (9)$$

$$F_{1,c}^H = \frac{g_{NN\pi}^2}{(4\pi)} I_\tau (2m_N^2) F_\pi(Q^2) \int_0^1 dx x^2 (1-x) \int \frac{d^2 K}{(2\pi)^2} \frac{1}{D(\vec{K}_+^2, x) D(\vec{K}_-^2, x)}, \quad (10)$$

where  $F_1$  and  $F_2$  are given as

$$F_i = \begin{cases} 2F_{i,a}^n + F_{i,a}^p, & \text{for the proton} \\ 2F_{i,a}^p + F_{i,a}^n, & \text{for the neutron} \end{cases}, \quad (11)$$

and  $g_{NN\pi}$  is the nucleon-pion coupling constant. In this work we take  $Zg_{NN\pi}^2/(4\pi) = 13.5$ .  $D$  is given as

$$D(l_\perp, x) = l_\perp^2 + x^2 m_N^2 + (1-x)m_\pi^2, \quad (12)$$

where  $\vec{L}_\pm = \vec{L}_\perp \pm \frac{1}{2} x \vec{q}_\perp$ . The nucleon-pion isospin coupling  $I_\tau$  is given as

$$I_\tau = \begin{cases} 2, & \text{for the proton} \\ -2, & \text{for the neutron} \end{cases}, \quad (13)$$

and  $\vec{K}_\pm = \vec{K}_\perp \pm \frac{1}{2} (1-x) \vec{q}_\perp$ .

Note that these equations are divergent and require a regularization prescription to render them finite. In this work, we choose to use a  $t$ -dependent form factor (with  $\Lambda$  the regulator mass parameter), given as

$$F(\vec{k}_\perp, x) = \exp \left[ -\frac{D(\vec{k}_\perp^2, x)}{(1-x)\Lambda^2} \right], \quad (14)$$

to regulate the formally divergent integrals. This choice corresponds to the preferred form of regulator in a recent study [27] of the origin of the  $\bar{d} - \bar{u}$  asymmetry in the proton arising from chiral effects [28, 29].

#### 4.1. $\Sigma$ Baryons

As explained earlier, we examine not only the chiral corrections to nucleon form factors but also to the  $\Sigma$  hyperons. The motivation for this lies in the recent work of Carrillo-Serrano *et al.* [17], which extended the earlier calculation of the nucleon electromagnetic form factors [16] to the baryon octet. Following the work of de Swart [30], under the assumption of  $SU(3)$  flavour symmetry, one has various relationships between the couplings of the baryons. The couplings relevant to this work are

$$g_{\Lambda\Sigma\pi} = \frac{2}{\sqrt{3}} (1-\alpha) g_{NN\pi}; \quad g_{\Sigma\Sigma\pi} = 2\alpha g_{NN\pi}, \quad (15)$$

where we set  $\alpha = 2/5$ . One may then show that the modifications to the above equations, in order to evaluate the hyperon form factors, are as follows:

$$m_N \rightarrow m_H, \quad (16)$$

$$F_i = 4 \left[ \frac{(1-\alpha)^2}{3} F_{i,a}^\Lambda + \alpha^2 F_{i,a}^{\Sigma^0} + \alpha^2 F_{i,a}^{\Sigma^-} \right], \quad (17)$$

$$I_\tau = 4 \left[ \frac{(1-\alpha)^2}{3} + \alpha^2 \right]. \quad (18)$$

Note that we take the  $\Sigma^0$  and  $\Lambda$  to be mass degenerate in the calculation of loop diagrams. The calculation of baryon electromagnetic form factors in this paper may be summarised as a two step process: firstly calculate bare electromagnetic form factors in the NJL Model (form factors without the effects of the pion cloud); secondly modify the bare form factors by incorporating pion cloud effects in an effective baryon-pion Lagrangian.

<sup>1</sup>A version of these equations also exists in [20], but there are several small changes in the definitions used here.

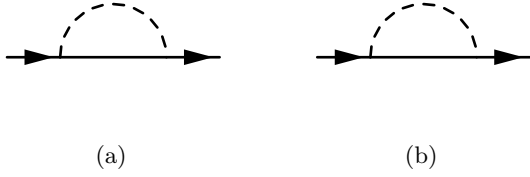


Figure 2: Pion contributions to the hadron self energy arise from the charged (2a) and neutral (2b) pion interactions.

#### 4.2. Incorporating the Self Energy

In calculating the chiral corrections, one is effectively including degrees of freedom previously absent from the system. These degrees of freedom modify bare quantities. In a self-consistent calculation, the inclusion of the pion cloud must also lead to corrections to other observables. In particular, the pion cloud also contributes to the baryon self energy, which is related to the bare baryon mass  $m^{(0)}$  via the well-known renormalisation condition

$$m_B = m_B^{(0)} + \Sigma(\not{p})|_{\not{p}=m_B}, \quad (19)$$

where  $m_B$  and  $m_B^{(0)}$  are the physical and bare masses of some baryon, and  $\Sigma(\not{p})$  is the self energy. As a consequence, the baryon masses in the bare NJL model should no longer be the physical masses but rather masses shifted such that with inclusion of the self-energy the physical baryon mass is obtained.

Using the effective field theory discussed above, the self energy contribution from the pion to the nucleon must be calculated. The relevant diagrams are shown in Fig. 2. The contribution where a form factor  $F$  has been used to regularize the loop integrals is:

$$\begin{aligned} \Sigma(\not{p} = m_N) = I_\tau \frac{Zg_{NN\pi}^2}{(4\pi)^2} \frac{1}{4m_N} \int_0^\infty dt \frac{t|F(-t)|^2}{(t + m_\pi^2)} \\ \times \left( \frac{t}{m_N^2} - \sqrt{\frac{t^2}{m_N^4} + \frac{4t}{m_N^2}} \right). \end{aligned} \quad (20)$$

Numerous studies within the cloudy bag model [31], Dyson-Schwinger equations [32] and lattice motivated studies of the  $\Delta - N$  mass difference as a function of quark mass [33], suggest that the self-energy contribution from the process  $N \rightarrow N\pi$  is of the order 100-150 MeV. As an illustration, we choose the regulator mass to fix this self-energy at 130 MeV (so  $\Lambda = 0.72$  GeV).

## 5. Results

The bare NJL Model used in the self-consistent evaluation of chiral corrections was calculated using the parameters in Table 1. This set was obtained by fitting the

$\Lambda_{IR}$	$\Lambda_{UV}$	$m_l$	$m_s$	$G_\pi$	$G_\rho$	$G_s$	$G_a$
0.24	0.67	0.35	0.52	14.53	8.12	4.11	3.14

Table 1: Chosen NJL model parameters, where all masses and regularization parameters are given in units of GeV, and the Lagrangian couplings in units of  $\text{GeV}^{-2}$ .

predicted baryon masses for the nucleon and  $\Xi$  to their experimental values. The resulting octet masses are shown in Table 2, Although the predicted values of the  $\Lambda$  and  $\Sigma$  masses differ slightly from the experimental values, as a result of an underestimate of the spin-spin interaction in the NJL model, the hierarchy of states is correct, that is,  $m_N < m_\Lambda < m_\Sigma < m_\Xi$ .

	$m_N$	$m_\Lambda$	$m_\Sigma$	$m_\Xi$
NJL- $\Sigma$	0.940	1.176	1.217	1.318
Experiment	0.940	1.116	1.193	1.318

Table 2: Calculated baryon octet masses (after including the hadron's self energy), compared with the experimental values (all in units of GeV).

This choice of parameters leads to a relatively good agreement between the predicted nucleon electromagnetic form factors and the empirical parameterization of Kelly [34], shown in Fig. 3. In particular, it is certainly of comparable quality to the previous NJL calculation, where the pion corrections were calculated at the parton level (coloured blue in plots).

As the pion contributes most at low  $Q^2$ , one may gauge the goodness of fit by comparing the predicted low energy observables with their experimental values. Table 3 shows the predicted electric charge radii of the studied baryons in comparison to both the previous NJL calculation (including pion loops on the valence quarks) and their respective experimental values. The present calculation produces an overall description of the nucleon and  $\Sigma^-$  charge radii of a similar quality to those generated in the earlier, parton level model. For the  $\Sigma^+$  we stress that the lattice QCD result for the charge radius still suffers some systematic uncertainties, as discussed in the original work.

Comparing the predicted and experimental magnetic moments in Table 4, we see that the proton magnetic

	$\langle r^2 \rangle^{\frac{1}{2}}$			
	$p$	$n$	$\Sigma^-$	$\Sigma^+$
Prev. NJL Calc.	0.87	0.38	0.86	0.97
LFCBM	0.89	0.41	0.78	0.88
Exp.	0.84 [37]	0.335	0.780	0.61(8) [36]

Table 3: Comparison of the predicted electric charge radii to experimental results for the proton, neutron,  $\Sigma^-$  and  $\Sigma^+$  baryons. Experimental results are taken from [34, 38, 37], except for the  $\Sigma^+$  charge radius, for which there is currently no experimental value. In this case, a recent lattice QCD result [36] is given instead. Charge radii are quoted in femtometres.

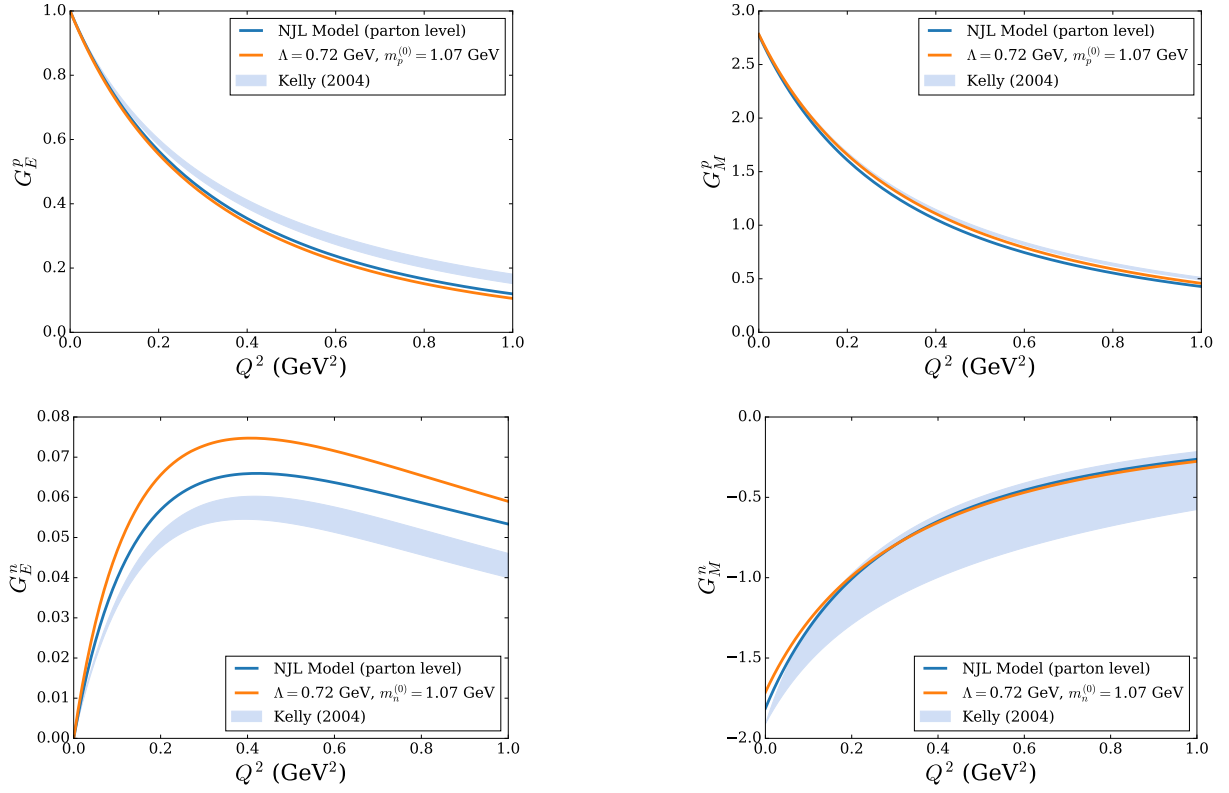


Figure 3: (Colour online) Electromagnetic form factors for the nucleon. The shaded region is obtained from uncertainties in the fitted parameters of Kelly's empirical model [34].

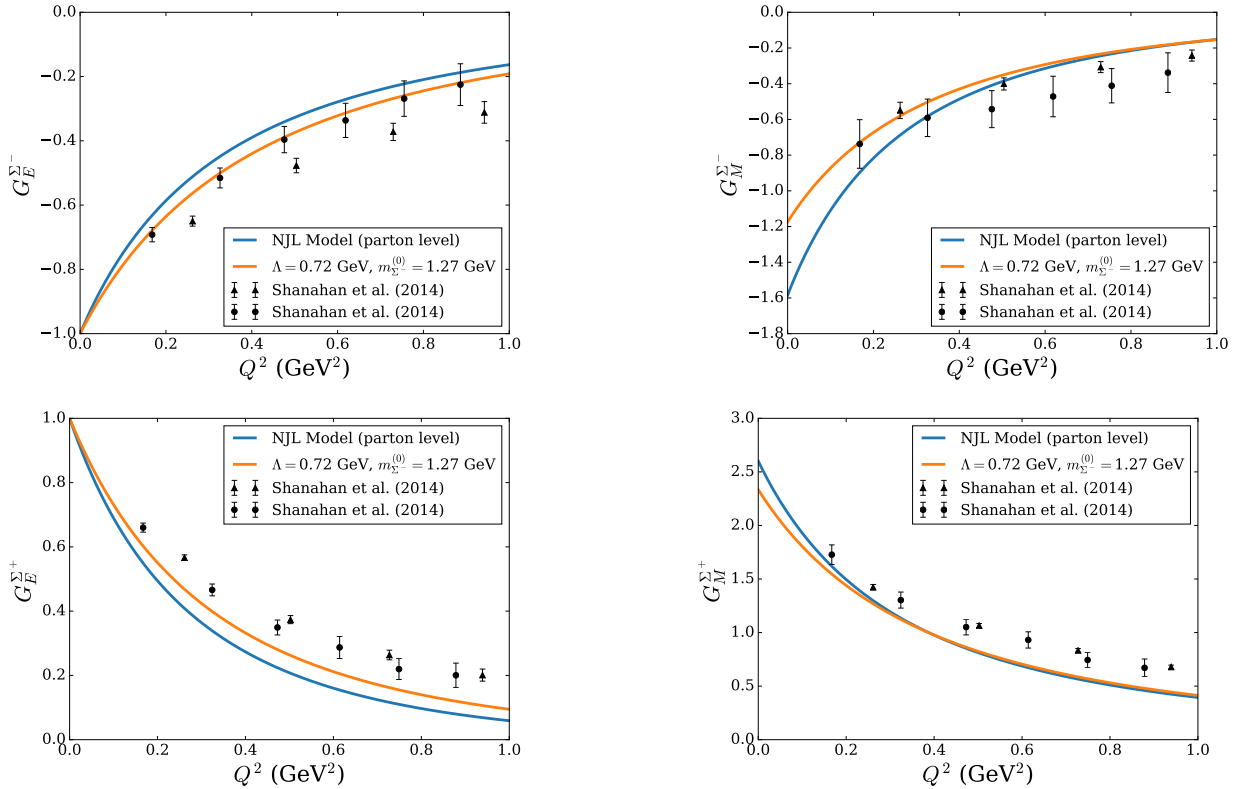


Figure 4: (Colour online) Electromagnetic form factors for the  $\Sigma^-$  and  $\Sigma^+$ . Points with error bars correspond to lattice results from [35, 36]. Note that the previous NJL calculation of the  $\Sigma^-$  magnetic moment gives a value of  $-1.58 \mu_N$ , while the method employed in this paper yields a value of  $-1.17 \mu_N$ . The experimental value is quoted as  $-1.16 \mu_N$ .

	$p$	$\mu$ $n$	$\Sigma^-$	$\Sigma^+$
Prev. NJL Calc.	2.78	-1.81	-1.58	2.60
LFCBM	2.78	-1.71	-1.17	2.33
Exp.	2.793	-1.913	-1.160(25)	2.458(10)

Table 4: Comparison of the predicted magnetic moments to experimental results for the proton, neutron,  $\Sigma^-$  and  $\Sigma^+$  baryons. Experimental results are taken from [34, 38]. Magnetic moments are in units of nuclear magnetons ( $\mu_N = e/2m_N$ ).

moment agrees with the experimental value, while the predicted neutron magnetic moment is slightly worse than the previous NJL Model prediction. The  $\Sigma^+$  magnetic moment shows a comparable level of agreement with experiment as the previous NJL model. However, it is for the  $\Sigma^-$  magnetic moment that one finds a remarkable difference when the chiral corrections are implemented correctly. Whereas evaluating the loops on individual quarks leads to  $\mu(\Sigma^-) = -1.58\mu_N$ , far larger than the empirical value ( $-1.160(25)\mu_N$ ), when implemented correctly at the hadronic level one finds  $\mu(\Sigma^-) = -1.17\mu_N$ , which is in excellent agreement with experiment. The reason for the overestimate in the  $\Sigma^-$  case is that the pion cloud on a  $d$ -quark dramatically increases its magnetic moment. The relative increase for a  $u$ -quark is also significant and all three quarks give a negative correction to the  $\Sigma^-$  as the valence  $u$ -quark has spin down.

Finally, we observe that for the  $\Sigma$  hyperon form factors up to 1 GeV<sup>2</sup> (shown in Fig. 4), the level of agreement between the calculations including pionic corrections at the hadronic level and recent lattice results including chiral corrections are typically as good as, or better than the calculations made at the quark level.

## 6. Conclusion

In this work we have investigated the practical importance of a correct implementation of chiral symmetry for the electromagnetic form factors of the nucleons and  $\Sigma$  hyperons. The NJL model was used to evaluate the form factors of the underlying quark structure, while the pion loop corrections were evaluated at the baryon level using the light-front cloudy bag model. The results were compared with experimental data where available, or with the results of a recent lattice QCD simulation to which chiral corrections had been applied if no experimental value existed.

Remarkably for the proton and neutron, there was little practical difference between the results of implementing the chiral corrections at the hadron or parton level. On the other hand, for the magnetic form factor of the  $\Sigma^-$ , there was a dramatic improvement when the pion corrections were evaluated correctly. In particular, the  $\Sigma^-$  magnetic moment is reduced by roughly 30% compared with an evaluation at the individual quark level, with the new result now in excellent agreement with experiment.

In summary, while it is convenient to evaluate pion loop corrections on individual quarks, independent of the hadronic environment, the results reported here illustrate very clearly that such an approach can deliver (at least for the hyperons studied) inaccurate results. Worse, there seems to be no obvious way to predict ahead of time whether or not the calculated values may be expected to be reliable. Hence, it is clear that a theoretically consistent, reliable result may only be obtained by performing the chiral corrections at the hadron level, as is done here.

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